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(21) Application No.	Patent application no. H7-121115	(71) Applicant	000005108 Hitachi Ltd. 4-6, Kanda-Surugadai, Chiyoda-ku, Tokyo
(22) Date of Application	May 19, 1995	(72) Inventor	Rudolf Von Bunao c/o Hitachi Central Research Laboratory 1-280 Higashi-Koigakubo, Kokubunji-shi, Tokyo
		(72) Inventor	Hiroshi Fukuda c/o Hitachi Central Research Laboratory 1-280 Higashi-Koigakubo, Kokubunji-shi, Tokyo
		(74) Agent	Katsuo Ogawa, patent attorney

(54) Title of the invention: Projection Exposure Method and Exposure Apparatus

(57) Abstract

Configuration: When a mask 1 is exposed and is projected onto a substrate 4 by a projection optical system 2, two diffraction gratings (A, B) are provided between the mask 1 and the projection optical system 2, and one diffraction grating C is provided between the projection optical system and the substrate so that an image of the mask pattern is reproduced near the substrate surface by the interference of light diffracted by the diffraction gratings.

Effects: By only inserting diffraction gratings in a space of a conventional exposure apparatus, it is possible to obtain an effect whereby the NA of an optical system is substantially doubled at the maximum. For this reason, it is possible to manufacture 0.1 μm-class LSI devices using reduction projection photolithography, which has a large exposure field and is suitable for mass production.

Scope of Patent Claims

Claim 1

A projection exposure method characterized in that the method comprises the steps of:

preparing a mask;

irradiating the mask with light from a light source;

diffracting a pattern of the mask; and

causing the diffracted light to be diffracted by a projection optical system and thus reproducing and exposing the mask pattern onto a sample.

Claim 2

The projection exposure method according to Claim 1, characterized in that the step of causing light to be diffracted involves two diffractions.

Claim 3

A projection exposure apparatus characterized in that the apparatus comprises:

a light source;

first and second diffraction means for irradiating a pattern on a mask with light from the light source and causing light from the mask to be diffracted;

a projection optical system that projects diffracted light onto a sample;

a third diffraction means for causing light from the projection optical system to be diffracted; and

a sample table on which the sample disposed below the third diffraction means is placed.

Claim 4

The projection exposure apparatus according to Claim 3, characterized in that the first and second diffraction means are phase gratings.

Claim 5

A projection exposure method in which a mask is irradiated with light having a wavelength λ emitted from a light source via an illumination optical system, and a pattern on the mask is imaged on a substrate by a projection optical system having a numerical aperture NA and a reduction ratio of M:1, thus forming the pattern on the substrate, the method characterized in that:

a first diffraction grating is provided between the substrate and the projection optical system in parallel to the substrate; and

two diffraction gratings of a second diffraction grating and a third diffraction grating are provided between the mask and the illumination optical system in parallel to the mask in that order from the mask side so that an image of the mask pattern is reproduced near a substrate surface by the interference of light diffracted by the first diffraction grating.

Claim 6

The projection exposure method according to Claim 5, characterized in that a cut-off spatial frequency f of an optical system provided with the diffraction gratings is higher than a cut-off spatial frequency f0 of an optical system without the diffraction gratings and is equal to or lower than twice the frequency f0.

Claim 7

The projection exposure method according to Claim 5, characterized in that a spatial period P1 of the first diffraction grating is in the range of $\lambda/(1.42 \cdot NA) \leq P1 \leq \lambda/NA$.

Claim 8

The projection exposure method according to Claim 5, characterized in that:

periodic directions of the first, second, and third diffraction gratings are the same, and a spatial period P1 of the first diffraction grating, a spatial period P2 of the second diffraction grating, and a spatial period P3 of the third diffraction grating are set so as to substantially satisfy a relationship of $1/P3=1/P2-1/(M \cdot P1)$.

[Claim 9]

The projection exposure method according to Claim 5, characterized in that: an optical distance Z1 of the first diffraction grating from the substrate surface and optical distances Z2 and Z3 of the second and third diffraction gratings from the mask surface are set so as to substantially satisfy a relationship of $(Z3-Z2)/P2=(Z3/M+Z1 \cdot M)/P1$.

[Claim 10]

The projection exposure method according to Claim 5, characterized in that:

the positions where the first, second, and third diffraction gratings are provided, the thicknesses of transparent substrates provided with the first, second, and third diffraction gratings, and the period of the second diffraction grating are set so as to minimize aberrations between the mask surface and an image plane according to the NA and reduction ratio of the projection optical system and the positional relationship between the respective diffraction gratings and the substrate.

[Claim 11]

The projection exposure method according to Claim 5, characterized in that: the spatial period P2 of the second diffraction grating is set so as to satisfy a relationship of $P2 \leq 1/(1-2 \cdot NA/M)$.

[Claim 12]

The projection exposure method according to Claim 5, characterized in that the second and third diffraction gratings are phase gratings.

[Claim 13]

The projection exposure method according to Claim 5, characterized in that the first diffraction grating is a phase grating.

Claim 14

The projection exposure method according to Claim 5, characterized in that:

a first light shielding pattern having a width of Z1·NA in the one direction and a spatial period of approximately 2·Z1·NA is provided between the substrate and the first diffraction grating; and

a second light shielding pattern for shielding a region that is substantially conjugated to the first light shielding pattern on the mask is provided right above or below the mask, thus limiting an exposure area, or causing the limited exposure area to be exposed by being scanned on the substrate or exposed while being moved in a stepwise manner.

Claim 15

The projection exposure method according to Claim 5, characterized in that:

the diffraction gratings are one-dimensional diffraction gratings; and

wavefront aberrations of the projection optical system are corrected so that they are linearly symmetrical on a pupil with respect to an axis of a diameter of the pupil perpendicular to the periodic directions of the diffraction gratings.

Claim 16

The projection exposure method according to Claim 5, characterized in that the mask includes a periodic phase shift mask.

Claim 17

The projection exposure method according to Claim 5, characterized in that the mask has a fine pattern in a certain direction according to the period and direction of the first diffraction grating.

Claim 18

The projection exposure method according to Claim 5, characterized in that a pattern shape of the mask is corrected according to the period and direction of the first diffraction grating.

Claim 19

The projection exposure method according to Claim 5, characterized in that liquid having a refractive index n larger than 1 is filled between the first diffraction grating and the substrate so that the NA of the projection optical system is set to be in the range of $0.5<NA<n/2$.

Claim 20

A projection exposure apparatus which includes an illumination optical system for irradiating a mask on a mask stage with light having a wavelength λ emitted from a light source, and a projection optical system having a numerical aperture NA and a reduction ratio of M:1, for causing a pattern on the mask to be imaged near the surface of a substrate on a substrate stage, the apparatus characterized in that:

a first diffraction grating having a first spatial period P1 ($\lambda/(1.42 \cdot NA) \leq P1 \leq \lambda/NA$) is provided between the substrate and the projection optical system in parallel to the substrate; and

two diffraction gratings of a second diffraction grating and a third diffraction grating are provided between the mask and the illumination optical system in parallel to the mask in that order from the mask side so that an image of the mask pattern is reproduced near the substrate surface by the interference of light diffracted by the first diffraction grating.

Claim 21

The projection exposure apparatus according to Claim 20, characterized in that:

periodic directions of the first, second, and third diffraction gratings are the same, and a spatial period P1 of the first diffraction grating, a spatial period P2 of the second diffraction grating, and a spatial period P3 of the third diffraction grating are set so as to substantially satisfy a relationship of $1/P3=1/(M \cdot P1)+1/P2$.

Claim 22

The projection exposure apparatus according to Claim 20, characterized in that:

the positions where the first, second, and third diffraction gratings are provided, the thicknesses of transparent substrates provided with the first, second, and third diffraction gratings, and the period of the second diffraction grating are set so as to minimize aberrations between the mask surface and an image plane according to the NA and reduction ratio of the projection optical system and the positional relationship between the respective diffraction gratings and the substrate.

Claim 23

The projection exposure apparatus according to Claim 20, characterized in that:

a light shielding pattern having a width of $Z1 \cdot NA$ in the one direction and a spatial period of approximately $2 \cdot NA \cdot Z1$ is provided between the substrate and the first diffraction grating; or

the apparatus includes a function of causing an exposure area limited by the light shielding pattern to be exposed by being scanned on the substrate or exposed while being moved in a stepwise manner.

Detailed Description of the Invention

[0001]

Industrial Field of Utilization

The present invention relates to a pattern forming method for forming a fine pattern of various solid-state devices and a projection exposure apparatus used for this method.

[0002]

Prior Art

Circuit patterns have become finer in order to improve the degree of integration and the operation speed of solid-state devices such as LSI devices. In addition, finer patterns are desired in order to achieve improvement in the properties of optical and electronic devices such as lasers, various quantum effect devices, dielectric and magnetic devices, and the like. Currently, in the formation of these patterns, a reduction projection exposure method which is excellent in mass producibility and resolution performance is widely used. Since the resolution limit of this method is proportional to the exposure wavelength and inversely proportional to the numerical aperture of the projection lens, improvement of the resolution limit was achieved by using the shorter wavelengths and the higher NA values.

[0003]

In addition, as a method for further improving the resolution of the reduction projection exposure method, various image enhancement methods such as a phase shift method, a modified illumination method (oblique incidence illumination method), or a pupil filtering method have been used. These methods aim at the effective use of performance of existing optical systems up to the theoretical diffraction limit (cut-off spatial frequency=$2NA/\lambda$). These image enhancement methods (frequently referred to as super-resolution methods) are discussed, for example, in Innovation of ULSI Lithography Technique, Chapter 1, Pages 34 to 49 (Published by Science Forum Co. Ltd, 1994, Tokyo).

[0004]

On the other hand, as a method of improving the resolution of a microscope to exceed the conventional diffraction limit, several methods that broaden the spatial frequency band of an optical system are known. These spatial frequency band broadening methods are discussed, for example, in Applied Physics, Vol. 37, Part 9, Pages 853 to 859 (1968). According to one of the methods, two grating patterns are scanned right above an object and an image (at least within a focal depth) while maintaining a conjugated relationship to form a moire pattern by the overlap of the object and the first grating pattern disposed right thereabove, and the moire pattern is caused to pass through a lens system to overlap the second grating pattern on an image side, whereby decoding is performed. Since the moire pattern has a spatial frequency lower than the object and the first grating pattern, it can pass through the lens system. A patent application which relates to a reduction projection exposure method using this method has already been filed. In general, since it is difficult to mechanically scan a grating pattern right above a wafer, a technique is used in which a photochromic material is provided directly on a wafer and scanned with an interference pattern overlapped thereon so that the material functions as a grating.

[0005]

Problems to Be Solved by the Invention

However, the conventional techniques described above have the following problems.

[0006]

First, it is considered that the wavelength of exposure light can be decreased only to that (193 nm) of an ArF excimer laser due to the problem associated with the transmittance of optical (lens) materials. In addition, it is considered that the NA of a projection optical system can be increased only to 0.6 to 0.7 due to the problem associated with the designing and manufacturing of lenses. However, the resolution limit of the conventional exposure method is generally about 0.5λ/NA, and is about 0.3λ/NA when a periodic phase shift method is used. Thus, even when the shortest wavelength and the highest NA value are used, it may be difficult to form a pattern of 0.1 μm or less. In addition, since a mask pattern that can be used with the periodic phase shift method is limited, an actual limit dimension of a general circuit pattern will be much greater than the above-mentioned dimension. In addition, although there is a demand to increase the size of an exposure area accompanied by the trend toward larger-scale LSI devices, it is very difficult to satisfy both demands for an increased exposure field and a higher NA value of the projection optical system.

[0007]

On the other hand, various spatial frequency band broadening methods that aim to overcome the conventional diffraction limit aim to enlarge a very small object using a microscope. For this reason, such methods have a problem in that they are not always suitable for forming a very small optical image demanded for photolithography. For example, in a method that uses the moire pattern, a mechanism or an optical system for allowing the two gratings to be scanned right above a mask and a wafer while maintaining a conjugated relationship will be very complicated. Since exposure of a resist is carried out with substantially evanescent light, there is a problem in that the light is attenuated in the wavelength range, making it difficult to expose a thick resist. In addition, there are very few materials that can be suitably used for the photochromic material. Thus, there is a problem in that the use of a photochromic material is not always practical considering mass production of LSI devices.

[0008]

An object of the present invention is to provide a projection exposure method of forming a fine pattern of various solid-state devices, which is capable of improving the resolution thereof to exceed the conventional diffraction limit (cut-off spatial frequency). Specifically, the present invention aims to provide a novel projection exposure method capable of obtaining an effect substantially equivalent to that when

the NA of a projection optical system is substantially doubled at the maximum without changing the NA and an exposure apparatus enabling the method.

[0009]

Another object of the present invention is to provide a projection exposure method which is capable of obtaining an effect of improving its resolving power by only adding a few of improvements to the structure of the conventional exposure apparatus and the optical system, and which is suitable for mass production of LSI devices satisfying both a large exposure field and a high resolution.

[0010]

Means to Solve Problems

The above-mentioned objects are attained by a configuration in which, when a pattern of a mask is imaged onto a substrate by a projection optical system (numerical aperture=NA, reduction ratio=1:M) using light having a wavelength λ to form the pattern on the substrate, a first diffraction grating having a spatial period P1 (where, preferably $\lambda/(1.42 \cdot NA) \leq P1 \leq \lambda/NA$) is provided between the substrate and the projection optical system in parallel to the substrate, and two diffraction gratings, i.e., a second diffraction grating and a third diffraction grating are provided between the projection optical system and the mask in parallel to the mask in that order from the mask side so that an image of the mask pattern is reproduced near the substrate surface by the interference of light diffracted by the first diffraction grating.

[0011]

In order to reproduce a faithful image of the mask pattern with the light diffracted by the first diffraction grating, the periodic directions of the first, second, and third diffraction gratings are set to be the same, and the spatial period P1 of the first diffraction grating, the spatial period P2 of the second diffraction grating, and the spatial period P3 of the third diffraction grating are set so as to substantially satisfy a relationship of $1/P3=1/P2-1/(M \cdot P1)$. In addition, an optical distance Z1 of the first diffraction grating from the substrate surface and the optical distances Z2 and Z3 of the second and third diffraction gratings from the mask surface are set so as to substantially satisfy a relationship of $(Z3-Z2)/P2=(Z3/M+Z1 \cdot M)/P1$. In addition, it is preferable that a relationship of $P2 \leq 1/(1-2 \cdot NA/M)$ be satisfied. In addition, it is preferable that the positions where the first, second, and third diffraction gratings are provided, the thicknesses of transparent substrates of the respective diffraction gratings, and the period of the second diffraction grating be set so as to minimize aberrations between the mask surface and an image plane. In addition, it is preferable that a first light shielding pattern having a width of $Z1 \cdot NA$ and a spatial period of approximately $2 \cdot Z1 \cdot NA$ be provided between the substrate and the first diffraction grating and that a second light shielding pattern for shielding a region that is substantially conjugated to the first light shielding pattern be provided right above or

below the mask, thus limiting an exposure area. In addition, if necessary, it is preferable that the limited exposure area be exposed by being scanned on the substrate, or exposed while being moved in a stepwise manner. The respective diffraction gratings are preferably phase gratings.

[0012]

The diffraction gratings are preferably one-dimensional diffraction gratings and wavefront aberrations of the projection optical system are corrected so that they are linearly symmetrical on a pupil with respect to an axis of a diameter of the pupil perpendicular to the periodic directions of the diffraction gratings. In addition, the present invention exhibits a particularly great advantage when a periodic phase shift mask is used as the mask. In addition, if necessary, it is preferable to limit the period or direction of the fine pattern or correct the pattern shape according to the periods and directions of the diffraction gratings. In addition, when liquid having a refractive index n larger than 1 is filled between the first diffraction grating and the substrate so that the NA of the projection optical system is set to be in the range of $0.5<NA<n/2$, it is possible to form a finer pattern.

[0013]

Action

The present invention aims to obtain an effect equivalent to that when an effective NA is increased by providing a diffraction grating between the final element of a projection optical system and a wafer and thus increasing an incidence angle of a light beam incident on a wafer plane. However, when the diffraction grating is provided simply between the lens of the conventional optical system and the wafer, the diffracted light that should be focused at one point on an image plane will be scattered at discrete positions on the image plane. Thus, it will be very difficult to reproduce the mask pattern. Therefore, it is necessary to reconstruct an optical system so that a faithful image of a mask pattern which is the source of interference is reproduced. In addition, from the perspective of practical use, it is preferable that these optical systems do not greatly change the conventional projection optical system and allow the use of the conventional mask. The present invention satisfies these demands as described later.

[0014]

In order to explain the operation of the present invention, the principle of imaging based on the present invention will be described in comparison with the conventional method. Imaging by an optical system based on an embodiment of the present invention is shown in FIG. 1. For comparison, the aspects of imaging by a conventional projection exposure optical system are shown in FIGS. 2a, 2b, 2c, and 2d showing the cases when a conventional mask or a phase shift mask was illuminated perpendicularly and obliquely, respectively. In any of the figures, it is

assumed that a 2:1 reduction optical system and a coherent illumination are used, and paraxial approximation was used.

[0015]

First, when the conventional mask is perpendicularly illuminated with the conventional optical system (FIG. 2a), light 22 that is perpendicularly incident on a transmissive mask 21 is diffracted by a pattern on the mask. Among the diffracted light, light beams having passed through a pupil 24 (the inside of an aperture 20) of the projection optical system 23 converge onto an image plane 25 and form a pattern by interference. Here, when a pattern period that gives the maximum diffraction angle of the light beams capable of passing through the pupil is defined as a resolution limit, the resolution limit will be $\lambda/(2NA)$ (where $NA=\sin\theta_0$). In addition, when a periodic phase shift mask 26 is used in this optical system, as shown in FIG. 2b, a 0th order diffracted light will disappear, and diffracted light beams appear symmetrical to an optical axis 29 (one-dotted line in the figure). For this reason, the maximum diffraction angle of the light beams capable of passing through the pupil is doubled, and the resolution limit is improved to $\lambda/(4NA)$.

[0016]

In addition, a case where an oblique illumination is used in the conventional optical system (FIG. 2c, in which it will be assumed that the 0th order light 27 of light diffracted from the mask passes through the left end of the pupil for simplicity's sake) will be described. In this case, among the light diffracted from the mask, either one of the components having a positive or negative diffraction angle about the 0th order light (in the figure, the +1st order light beams 28) pass through the pupil and converge onto the image plane. Since the diffracted light beams having a diffraction angle twice that of the case of perpendicular incidence are capable of passing through the pupil, the resolution limit will also be $\lambda/(4NA)$. However, since only one side of a diffraction spectrum is used, the resolution of an isolated pattern will not be changed from that of the case of perpendicular illumination, and there is also a problem in that a contrast decreases for the periodic pattern. In addition, when the mask is changed to the periodic phase shift mask 26, since a plurality of diffracted light beams will be unable to pass through the pupil, the pattern is not resolved (FIG. 2d).

[0017]

Next, imaging by the optical system based on an embodiment of the present invention is shown in FIG. 1. The optical system shown in FIG. 1 has a configuration in which in the conventional optical system shown in FIG. 2, a diffraction grating A and a diffraction grating B are inserted between a mask 1 and a projection optical system 2, and a diffraction grating C is inserted between the projection optical system 2 and a wafer 4. Here, the diffraction gratings A, B, and C are phase gratings.

[0018]

Light R perpendicularly incident on the mask 1 is diffracted on the mask surface, and the 0th order diffracted light R0, the +1st order diffracted light R1, and the -1st order diffracted light R1' are generated. The 0th order light R0 reaches a point A0 on the diffraction grating A, and light diffracted in the -1st order direction at that point is diffracted in the +1st order direction at a point B0 on the diffraction grating B. Then, the diffracted light passes through the left end of a pupil 3 (the inside of an aperture 5) and is diffracted in the ±1st order directions at a point C0 on the diffraction grating C. The diffracted light beams reach two points Q and P on an image plane, respectively. In addition, the +1st diffracted light R1 reaches a point A1 on the diffraction grating A, and light diffracted in the -1st order direction at that point is diffracted in the +1st order direction at a point B1 on the diffraction grating B. Then, the diffracted light passes through the right end of the pupil 3 and is diffracted in the ±1st order directions at a point C1 on the diffraction grating C. The diffracted light beams also reach the points Q and P on the image plane. On the other hand, the light paths of the 0th order light R0' and the -1st order diffracted light R1' which are diffracted in the +1st order direction at the point A0 are symmetrical to the optical paths of the two light beams with respect to an optical axis 6 (one-dotted line in the figure). That is to say, both light beams will be eventually diffracted in the ±1st order direction at the point C0 on the diffraction grating C and reach the point P and Q' on the image plane. Therefore, the three light beams, i.e., the 0th order light beam, and the +1st and -1st light beams which have been diffracted from the mask meet on the point P. It is obvious that they do not depend on the diffraction angle of the mask. Therefore, a faithful diffraction image will be reproduced at the point P.

[0019]

When compared to the conventional method (FIG. 2a), since the diffracted light having a doubled diffraction angle is allowed to pass through the pupil using an optical system having the same NA and magnification ratio, it is possible to obtain an effect equivalent to that when the NA is substantially doubled. In addition, in the case of oblique illumination (FIG. 2b), only one of the diffracted light beams on the negative and positive sides of the 0th order light can be reproduced on the image plane. On the contrary, in the case of the present invention, since the diffracted light beams on both sides can be reproduced on the image plane, it is possible to improve the resolution of an isolated pattern, which was difficult in the oblique illumination, and to obtain a high contrast for the periodic pattern. In addition, when the periodic phase shift mask is used in the present optical system (FIG. 3a), the 0th order diffracted light will disappear, and the +1st order light R+ and the -1st order light R- having a diffraction angle that is twice the normal diffraction angle will interfere with each other. As a result, the minimum resolution will be $\lambda/(8NA)$. This corresponds to 1/2 of $\lambda/(4NA)$ which hitherto has been considered to be a theoretical limit when the

periodic phase shift mask or an oblique illumination was used, and the resolution is dramatically improved by the present invention. In addition, the aspect of imaging when oblique illumination is used in the present optical system is shown in FIG. 3b. With the oblique illumination, it is possible to allow the diffracted light R1" having a large diffraction angle on only one side to pass through the pupil, and the resolution can be improved by a maximum of twice, namely λ/(8NA), which is that of the case of perpendicular illumination. In addition, when various types of illumination light having different mask incidence angles are used, it is possible to obtain the effect of a partially coherent illumination which is perfectly similar to the conventional optical system.

[0020]

From the perspective of Fourier diffraction theory, the principle of the present invention can be explained as follows (FIG. 4). In the following description, it will be assumed that the magnification ratio of an optical system is 1, the diffraction gratings are one-dimensional phase gratings, and only the ±1st order diffracted light will be considered. When the pupil 3 is viewed from the point P on the image plane via the diffraction grating C, the pupil appears to be divided in two due to diffraction (FIG. 4a). In the respective pupils, mask Fourier transform images that pass through the pupil at a certain angle are seen. On the other hand, when considered from the mask side, light diffracted by the mask is diffracted by the diffraction gratings A and B to form a plurality of mask Fourier transform images on the pupil. Among the images, images that passed through the pupil at a certain angle are seen in the pupil that was seen in the above (FIG. 4b). That is to say, in FIG. 4, the Fourier diffraction image on the right of FIG. 4b is seen in the pupil on the left of FIG. 4a, and the Fourier diffraction image on the left of FIG. 4b is seen in the pupil on the right of FIG. 4a. In this case, the following two conditions should be satisfied for images to be properly reproduced at the point P.

[0021]

(1) The spectrum at the same point on the mask should be seen via the two pupils.

[0022]

(2) Two spectra should be connected continuously at a contact point of the two pupils.

[0023]

In other words, it is necessary to ensure that one continuous spectrum can be seen via a plurality of pupils.

[0024]

As viewed from an image, if a plurality of pupils shifted by f' can be seen via the diffraction grating C, and a plurality of Fourier diffraction images shifted by f'

can be seen in the respective pupils via the diffraction gratings B and A, the amplitude distribution u(x) of a true image can be expressed by the following expression.

[0025]

$$u(x)=F[\Sigma p(f-f')\cdot\Sigma o(f-f'')]$$
$$f'=\pm SC$$
$$f''=\pm(SA-SB-SC)$$

Here, F[] is a Fourier transform, p(f) is a pupil function, o(f) is a mask Fourier transform image, x is an actual spatial coordinate, f is a spatial frequency coordinate, SA, SB, and SC are sin (sinusoidal) of the diffraction angles of the diffraction gratings A, B, and C, and Σ is the sum of other diffraction orders. Therefore, if SA=SB+SC, then f"=0. Thus, it is possible to obtain a term where f"=0 for both f'=±SC. That is to say, it is possible to see one spectrum o(f) via two pupils p(f±SC). In addition, in order to obtain an image of the same point on the mask at the point P, it may be helpful that the distances ZA and ZB between the mask surface and the diffraction gratings A and B and the distance ZC between the diffraction grating C and an ideal image plane are set so as to satisfy a relationship of SA·(ZB-ZA)=SC·(ZB+ZC).

[0026]

When the above conditions are applied to an optical system having a reduction ratio of M:1 and an image-side numerical aperture of NA under paraxial approximation, it is known that it is helpful to set the periods PA, PB, and PC of the diffraction gratings A, B, and C, the distances ZA and ZB between the mask surface and the diffraction gratings A and B, and the distance ZC between the diffraction grating C and the image plane so as to substantially satisfy the following relationship.

[0027]

$$1/PA=1/PB-1/(M\cdot PC)$$
$$(ZB-ZA)/PA=(ZB/M+M\cdot ZC)/PC$$

In addition, in order to obtain a sufficient resolution improving effect with the present invention, it is preferable to satisfy a relationship of $\lambda/NA\leq PC\leq\sqrt{2}\cdot\lambda/NA$

[0028]

The diffraction gratings A and B are preferably phase gratings. If the diffraction gratings A and B are not perfect phase gratings but transmit the 0th order light, the effect of the conventional optical system or the oblique incidence optical system which has inferior resolution than the present method may overlap the effect of the present method. For this reason, there is a concern that the resolution deteriorates. On the other hand, the diffraction grating C may be a phase modulation grating or an amplitude intensity modulation grating. The period of the diffraction grating C is very small, and if a silicon oxide film having a refractive index of 1.5 is used, the sectional aspect ratio of the grating pattern is approximately 1. In this case, it is necessary to carefully control light scattering on the pattern section. If the

diffraction grating is formed of a light shielding pattern, since the light shielding film can be made to be very small, the influence of scattering can be reduced. However, as will be described later, the use of a phase modulation grating can better increase the size of exposure area.

[0029]

When the substrate side of the diffraction grating B is filled with liquid having a refractive index n larger than 1, the sin of a diffraction angle and the wavelength of this region become 1/n. Here, when the period of the diffraction grating B is decreased further and the diffraction angle is made to be similar to the case where liquid is not filled, since only the wavelength becomes 1/n, the resolution is also improved to 1/n. In this case, on the mask side, it is necessary to increase a mask illumination angle so that diffracted light having a larger diffraction angle can pass through the pupil. However, diffracted light having a small diffraction angle cannot pass through the pupil. Therefore, it is desirable to increase the diameter of the pupil according to this. This can be rephrased as follows. If the refractive index between the diffraction grating B and the substrate is 1, even when the NA of a projection optical system used in the present invention is set to 0.5 or higher, no improvement of resolution can be obtained. If the diffraction angle of a light beam incident on the diffraction grating B having a period of λ/NA at an incidence angle θ whose $\sin\theta>0.5$ is 90° or larger, the light beam will become an evanescent wave appearing in a local area on the surface of the diffraction grating and will not be transmitted to the wafer. On the other hand, if the refractive index n between the diffraction grating B and the substrate is n, the diffraction angle θ' of light incident on the diffraction grating B at an incidence angle whose $\sin\theta=NA$ satisfies a relationship of $\sin\theta'=(\lambda/PB+\sin\theta)/n=2NA/n$ (In this case, the diffraction grating B must have a period of λ/NA in order for the 0th order light having passed through an end of the pupil to be perpendicularly incident on the wafer). The condition for $\theta'<90°$ is $NA<n/2$. That is to say, the present invention can be effectively applied to an optical system whose $NA=n/2$ at the maximum. Although a liquid immersion optical system generally requires a special optical design, when it is applied to the present invention as described above, no special lens is required. Therefore, when exposure is performed with water (refractive index: about 1.3) between the substrate and the diffraction grating B using a projection lens having an NA of about 0.6, which is typically used in the semiconductor process, it is possible to obtain an effect equivalent to that when the NA is substantially 1.2. In this case, when a phase shift mask is used, a resolution of 0.1 μm or less can be obtained even at the wavelength (365 nm) of the i-ray of a mercury lamp. In addition, in the present method, since the incidence angle of light interfering near the wafer is very large, the imaging performance greatly depends on the polarization state of light. In general, light in

which an electric field vector has a perpendicular polarization state to an incidence plane of light is preferable for formation of a high-contrast image.

[0030]

All the discussions above were made under the paraxial approximation, assuming that the refractive index of the diffraction grating substrate is 1. However, in fact, the effect of the refractive index of the diffraction grating substrate or the effect of aberrations resulting from the diffraction grating should be strictly considered. For this reason, the positions where the respective diffraction gratings are provided may be slightly changed. Needless to say, it is preferable that the periodic directions of a plurality of diffraction grating patterns be made identical with a sufficient precision.

[0031]

Next, four points that should be noticed in the present invention will be mentioned.

[0032]

The first point is that in the present optical system, the exposure area is generally limited compared to the conventional exposure method. As can be seen from FIG. 1, two light beams meet also at points Q and Q' on the image plane and interfere with each other to form images. These images are spurious images that are formed at positions different from an intended position where they should be formed and are generally undesirable. In order to obviate this, as shown in FIG. 5a, it is preferable to provide a light shielding mask 52 right above an image plane 51 (between the wafer and the diffraction grating C) so as to block these spurious images. As shown in the figure, the diffraction grating C and the light shielding mask 52 can be formed on both sides of a same crystal substrate 53 (they may be formed on different substrates). In addition, at the same time, similarly, it is desirable that a masking blade for shielding a region that is substantially conjugated to the light shielding mask be provided right above or below the mask, thus limiting a mask illumination region to the conjugated region. An exposure area that can be transferred by one exposure operation occurs repeatedly in a region corresponding to the distance (approximately $2 \cdot NA \cdot ZB$) between the true image (P point) and the spurious image (Q point), and the repetition period is twice the distance. Therefore, if an exposable area is narrower than a desired exposure area, as shown in FIG. 5b, it is preferable to scan the exposure area on the wafer. In this case, it goes without saying that if the reduction ratio of an optical system is M:1, it is preferable that the ratio of a mask scan speed to a wafer scan speed be strictly M:1. As for a method of scanning these exposure areas in a synchronized manner on the mask and the wafer, a method used in an existing exposure apparatus can be used. On the other hand, if an exposable area is larger than a desired exposure area, namely if the distance between the true image and

the spurious image can cover one chip, for example, the exposure area can be exposed without scanning. The size of the exposure area is determined by the position where the diffraction grating B is provided, and the width of one exposure area increases as the diffraction grating B is further from the image plane. However, since the width of an area that cannot be transferred also increases, the ratio of both values remains unchanged at approximately 1:1. In order to obviate the influence of spurious images, it is preferable that the width W of the exposure area on the wafer be set so as to satisfy a relationship of $W \leq NA \cdot ZB$. In addition, when an amplitude intensity modulation grating is used for the diffraction grating B, since the 0th order diffracted light of the grating will form another spurious image at a midpoint of the true image and the spurious image, the exposure area will be nearly half that of the phase grating.

[0033]

The second point is that in the present method, exposure intensity generally decreases. A light beam imaged on a wafer with the present method uses only a particular diffraction order light among the light beams diffracted by the diffraction grating inserted in the optical system. Therefore, the light intensity contributing to exposure will decrease as the number of times the light passes through the diffraction grating increases. In addition, as described above, the fact that the exposure area is limited on the mask and the wafer serves as the cause of decreased throughput. For this reason, in the present method, it is preferable to take measures, for example, the use of a light source having sufficient intensity and the use of a resist material such as a chemically amplified resist having high sensitivity.

[0034]

The third point is that as described above, in addition to a desired diffraction image of $f'=0$, Fourier transform images shifted by $f'=\pm 2(SA+SB)$ are also formed on the pupil. This means that higher-order spectra of the mask pattern overlap with a substantially low spatial frequency region, which is generally undesirable. In order to obviate this, it may be helpful to set the optical system shown in FIG. 1 so as to satisfy a relationship of $PA \leq 1/(1-2 \cdot NA/M)$.

In this case, among the diffracted light (R1 in FIG. 1) diffracted by the mask at a diffraction angle of $2 \cdot NA/M$, a diffracted light beam (corresponding to a dotted line starting from a point A1 in FIG. 1) that is diffracted in the +1st order direction by the diffraction grating A cannot exist.

[0035]

The fourth point is that in the optical system of the present invention, it is necessary to carefully control aberrations accompanied by the introduction of diffraction gratings. The aberrations generated by the diffraction gratings will be described with reference to FIG. 6. It will be assumed that a light beam having passed through the mask is present in a plane including the optical axis and the periodic

directions of the diffraction gratings (for example, one-dimensional pattern and a coherent illumination are used). In order to ensure that an optical system shown in FIG. 6a is stigmatic, a difference between respective optical paths $OX_1X_2X_3I$, $OY_1Y_2Y_3I$, and $OZ_1Z_2Z_3I$ must be 0. However, if there is an optical path difference between them, this difference appears as an aberration. Here, if it is assumed that a projection optical system is an ideal optical system having an aberration of 0, since $X_2X_3=Y_2Y_3=Z_2Z_3$, a difference between $OX_1X_2+X_3I$, $OY_1Y_2+Y_3I$, and $OZ_1Z_2+Z_3I$ will be an aberration. A wavefront aberration of an optical path that crosses the diameter of a pupil and extends from $OX_1X_2X_3I$ to $OZ_1Z_2Z_3I$ can be plotted as the solid line in FIG. 6b when the aberration is plotted on the pupil's radius coordinate s that is normalized based on $OY_1Y_2Y_3I$. It is known that an aberration w+(s) of a light beam having passed through the mask and having a positive angle with respect to the optical axis is generally asymmetrical on the pupil. Similarly, an aberration w-(s) of a light beam having a negative angle with respect to the optical axis will be symmetrical about the aberration w+(s) and the pupil because of the symmetry of the optical system. In the present invention, since it is necessary to cause a light beam diffracted in the positive direction and a light beam diffracted in the negative direction to simultaneously interfere with each other on the wafer, it is necessary to correct the aberrations of both light beams at the same time. However, as can be seen from FIG. 6b, since the aberrations on the pupil, of the light beams diffracted in the positive and negative directions are not identical, it is in principle difficult to correct these aberrations at the same time with the projection optical system. Therefore, it is preferable that these aberrations be corrected between the mask and the projection optical system or between the wafer and the substrate. This correction can be generally performed by the following method.

[0036]

If w+(s) and w-(s) are identical, they can be corrected by the projection optical system. Therefore, it may be helpful to suppress $\Delta w(s)=\{w+(s)\}-\{w-(s)\}$ to an amount δ that is sufficiently small compared to the wavelength on the pupil (in FIG. 6, in the range of $-1\leq s\leq 1$). On the other hand, $\Delta w\pm(s)$ is expressed as a function of parameters xi (i=1, 2, ...) such as the positions and periods of the respective diffraction gratings, the thicknesses and refractive indices of substrates supporting the diffraction gratings, the relative positional relationship between the substrates and the diffraction gratings, and the like. Here, the question reduces to how the xi satisfying a relationship of $\Delta w(s,xi)<\delta$ can be calculated within the range of $-1\leq s\leq 1$. An example of practical optimization will be described in the section of Examples. In any case, in this manner, when the aberrations of light beams having passed through the mask and having positive and negative angles with respect to the optical axis are made to be symmetrical on the pupil, it is possible to correct the aberrations in the projection

optical system. In addition, it will be more preferable if the aberrations themselves can be suppressed sufficiently by the method described above.

[0037]

Hereinabove, the mask pattern has been considered to be a one-dimensional pattern for the simplicity's sake. However, actually, when a two-dimensional pattern is present or a partially coherent illumination is used, the light beams having passed through the mask will not converge on a plane including the optical axis and the periodic directions of the diffraction gratings but will be directed to various points on the pupil. In this case, it may be helpful to consider a function $\Delta w(s,t)=\{w+(s,t)\}-\{w-(s,t)\}$ of a two-dimensional coordinate (s,t) on the pupil as the Δw and calculate the xi satisfying a relationship of $\Delta w(s,t,xi)<\delta$. This means that the $w\pm(s,t)$ is made to be as symmetrical as possible with respect to s=0.

[0038]

In addition, in order to obtain the effect of the present invention in all directions, for example, it may be considered to use two-dimensional diffraction gratings as the respective diffraction gratings as shown in FIGS. 7a and 7b. In this case, the shape of an apparent pupil is symmetrical at four times. However, due to the reasons mentioned above, it is a little difficult to correct the aberrations on two perpendicular pupils at the same time unless the NA of the optical system is small. For this reason, it is a little difficult to obtain the effect of the present invention equally in all directions on the mask, and it may be more practical to use one-dimensional diffraction gratings as shown in FIG. 8. FIGS. 8a, 8b, and 8c show three typical diffraction gratings and the shapes of apparent pupils. In the case of FIG. 8a, the effective NA increases nearly twice for an x-directional pattern, whereas it decreases for a y-directional pattern. In the case of FIG. 8b, the effective NA increases by $\sqrt{2}$ times for an x-directional pattern, whereas it decreases by 1/2 for a y-directional pattern. In the case of FIG. 8c, the NA increases by $\sqrt{2}$ times for both x and y-directions, whereas it is considered that the imaging performance in directions other than the x and y-directions greatly depends on the pattern direction. In any of the cases, it is preferable to put limitations based on directions to a layout rule or the like of a pattern on the mask.

[0039]

In order to obviate the dependency of imaging performance on the pattern direction, a method may be used in which the conditions of FIGS. 8a, 8b, and 8c are rotated by 90°, for example, and are subjected to multiple exposures. In particular, when this method is applied to FIG. 8c, it is possible to suppress the dependency on the pattern direction other than the x and y-directions and obtain an image equivalent to that when the NA increases by $\sqrt{2}$ times for both x and y-directions without sacrificing an image contrast. However, when the diffraction grating is rotated by

90°, the aberration characteristic is also rotated by 90°. Therefore, it is preferable to take measures, for example, correcting aberrations using a pupil filter and rotating the pupil filter by 90° together with the diffraction gratings. In addition, when it is difficult to suppress aberrations, a slit filter or the like may be provided on the pupil, if necessary.

[0040]

As shown in FIG. 3, when the periodic phase shift mask is illuminated by a perfect coherent illumination, the optical paths of the ±1st order light beams interfering near the wafer are always symmetrical to the optical axis, and the respective optical path lengths are the same. Therefore, even if the aberrations of an optical system are not corrected, it is possible to form a fine pattern. That is to say, when a periodic phase shift mask is used under a perfect coherent illumination, it is possible to use the two-dimensional diffraction gratings as shown in FIG. 7 and make the most of the effect of the phase shift mask regardless of the pattern directions. When a mask pattern in which various patterns are mixed up is transferred, it may be helpful to expose only a fine periodic pattern by the above-described method and expose the other portions by the conventional exposure method.

[0041]

In addition, the above-mentioned aberrations generally increase abruptly with the NA values. For this reason, such aberrations are not serious problems in an optical system having an NA of about 0.1 to 0.2. Therefore, when the present invention is applied to a low-NA, low-magnification, large-scale exposure apparatus, a reflective soft X-ray reduction projection exposure apparatus, or the like, various restrictions mentioned above are diminished.

[0042]

It can be said that the idea of the present invention is to cause the Fourier diffraction images on the left and right sides of the 0th order diffracted light to individually pass through the pupil and combine the images on an image side. Although this idea itself is already applied in an optical microscope as discussed in the above-mentioned documents, a structure of an optical system that enables this idea to be implemented on a reduction projection optical system has not been devised hitherto. The present invention is neither more nor less than an adept implementation of this idea in a reduction projection exposure system. That is to say, the optical system shown in FIG. 1 has a configuration in which diffraction gratings are provided between a projection optical system and a wafer so that an incidence angle of a light beam incident on a wafer plane is increased, and a faithful image is reproduced on a mask pattern which is the source of interference on the wafer plane. The present invention can be applied to various projection optical systems such as a refractive optical system, a reflective optical system, and a combination thereof, and a

magnification optical system such as a reduction optical system. As an exposure method of exposing a mask pattern on a wafer using these optical systems, the present invention can be applied to any method such as a batch transfer method, a scanning method, a step-and-repeat method, or a step-and-scan method. In addition, as is obvious from the above description, the present invention is purely based on a geometric optical effect. Therefore, the problems resulting from the use of evanescent light in the above-described method of using a moire pattern will not occur. In addition, since the diffraction gratings can be provided at positions distant from the wafer, and there is no need to perform synchronized scan, the present invention can be implemented much more easily.

[0043]

Examples

Example 1

Based on the present invention, a scanning KrF excimer laser projection exposure apparatus in which the NA is 0.45, the light source wavelength λ is 248 nm, and the reduction ratio is 4:1 was modified as schematically shown in FIG. 9. That is to say, a transparent crystal substrate 103 having a phase grating pattern on both surfaces was inserted between a mask 101 mounted on a mask stage 100 and a projection optical system 102. In addition, a transparent crystal substrate 106 having a light shielding pattern on one surface and a phase grating pattern on the other surface was inserted between a wafer 105 mounted on a wafer stage (sample table) 104 and the projection optical system 102 so that the side of the light shielding pattern faces the wafer. A Cr pattern having a width of 300 μm and a period of 1 mm was used as the light shielding pattern, and a Si oxide film pattern having a period of λ/NA was used as the phase grating pattern. The period of the phase grating pattern on the mask-side transparent crystal substrate 103 was four times that of the wafer-side phase grating pattern. The Si oxide film thickness was set so that a phase difference between the respective light beams having passed through a film-presence portion and a non-presence portion was 180°. These patterns were formed using EB lithography similar to the process of manufacturing a so-called chromeless phase shift mask. In addition, a transparent crystal substrate 108 having a light shielding pattern having a width of 1.2 mm and a period of 4 mm was provided on the side of the mask close to an illumination optical system 107. A light shielding region of the light shielding pattern was set so as to be conjugated to the light shielding pattern on the wafer-side transparent crystal substrate 106.

[0044]

The periods of the phase gratings on both surfaces of the transparent crystal substrate 103, the film thicknesses and positions of the respective transparent crystal substrates, and the like were optimized using an optimization function of a light beam

tracking program so that in the context mentioned in the section of Action, the aberrations on the pupil of the projection optical system are axially symmetrical. In addition, an aberration correction filter 109 was inserted at the position of the pupil of the projection optical system in order to correct the axially symmetrical aberrations. Here, the aberration correction filter 109 mainly corrects astigmatism in a direction perpendicular to the periodic directions of the diffraction gratings. The transparent crystal substrates having the diffraction gratings and the like and the aberration correction filter were configured such that they can be replaced and set to predetermined positions quickly. In addition, in order to achieve accurate positioning of the transparent crystal substrates, a holder (not shown) of each crystal substrate may have a micro drive mechanism (not shown) to measure the position of each crystal substrate so that the crystal substrate is set to a desired position. In addition, an image was monitored on an autofocus monitor (not shown) provided on the wafer stage 104, and monitoring results were fed back so that an optimum imaging characteristic was obtained on the image plane, and the positions of the crystal substrates can be adjusted. The aberrations of the projection optical system itself with respect to the diffraction gratings may be corrected in advance, and in this case, the aberration correction filter is not necessary. The exposure was performed by scanning the mask and the wafer in a synchronized manner. A stage control system 110 scans the mask stage 100 and the wafer stage 104 in a synchronized manner at a speed ratio of 4:1.

[0045]

Using the exposure apparatus, a mask having patterns of various dimensions including a periodic phase shift pattern was transferred onto a chemically amplified positive resist. A predetermined developing process was performed after the exposure, and the resist was observed using a scanning electron-beam microscope. The results of observation showed that it was possible to form a resist pattern having a dimension of 90 nm (period: 180 nm) with respect to the periodic directions (x-direction) of the phase gratings by the periodic phase shift mask. On the other hand, the resolution in a direction (y-direction) perpendicular to the direction was about 140 nm (period: 280 nm) using the phase shift mask. Subsequently, the three phase gratings and the aberration correction filter were rotated by 90°, and the same mask was exposed to form a resist pattern. The resolutions in the x and y-directions were reversed.

[0046]

In the above example, although the type, NA, light source wavelength, and reduction ratio of the optical system, the types and dimensions of the resist and mask pattern, the periods and positions of the diffraction gratings and light shielding pattern

are particularly limited, these various conditions may be changed in various ways within the scope without departing from the spirit of the present invention.

[0047]

Example 2

Next, an example of optimization of an optical system so that the influence of an aberration accompanied by introduction of diffraction gratings becomes the minimum will be described. In an optical system shown in FIG. 10, O and I are a mask surface and an image plane of an optical system, respectively, in which diffraction gratings are introduced, Σ and Σ' are a mask surface and an image plane of a projection optical system in which diffraction gratings are not introduced, and h_i (i=1 to 6) are distances in the figure. The diffraction gratings A, B, and C, and the light shielding pattern right above the wafer were formed on both surfaces of a transparent crystal substrate similarly to Example 1. In this case, transverse aberrations $w\pm(s)$ of light beams having passed through the mask and having positive and negative angles with respect to the optical axis can be expressed by the following expressions as a function of a normalized pupil radius coordinate s.

[0048]

$$w\pm(s)=wu\pm(s)+ws\pm(s)$$
$$wu\pm(s)=C_1h_1+C_2(s_1)h_2+C_5h_5+C_6h_6$$
$$ws\pm(s)=C_3h_3+C_4h_4$$
$$C_1=\tan[(s\pm s_0)/M]/M,$$
$$C_2=\tan[\pm(s_1/n)-(s\pm s_0)/(nM)]/M,$$
$$C_3=\tan[s/M]/M,$$
$$C_4=\tan(s),$$
$$C_5=\tan[(s\pm s_0)/n],$$
$$C_6=\tan(s\pm s_0)$$

Here, wu is a component that is asymmetrical to s=0 on the pupil, and ws is a component that is symmetrical. In this case, s_0=NA and $s_1=\lambda/PA$. If s_0(NA), reduction ratio M, refractive index n of transparent crystal substrate are values unique to a system, the above expression includes seven optimization parameters, i.e., h_i (i=1 to 6) and s_1. These values were optimized by applying seven constraint conditions so that the aberrations $wu\pm(s)$ and $ws\pm(s)$ were minimized. An example of optimization results for several NA values is shown in Table 1. In this case, aberrations shown are wavefront aberrations whose unit is h_5/λ.

[0049]

Table 1

NA	0.1	0.2	0.3	0.4
h_1/h_5	17.352	16.167	14.263	11.343
h_2/h_5	0.529	0.995	1.343	1.507
h_3/h_5	24.014	22.800	20.137	14.819
h_4/h_5	0.368	0.485	0.652	0.920
h_6/h_5	0.01	0.01	0.01	0.01
s_1	1.225	1.259	1.300	1.349
$w_{max}(s)$	5×10^{-9}	3×10^{-7}	4×10^{-6}	5×10^{-6}
$w^{u}_{max}(s)$	1×10^{-12}	1×10^{-9}	2×10^{-7}	1×10^{-5}

$$w^{u}_{max}(s) = \max[w+(s) - w-(s)]$$
$$s1 = n\lambda/PA$$

[0050]

As can be seen from the table, it was possible to sufficiently suppress the aberration at NA=0.4. Similar optimization can be performed for various layouts such as a case where the diffraction gratings A and B are provided on different transparent substrates. In addition, stricter aberration conditions can be satisfied by increasing the number of optimization parameters by introducing another transparent substrate or diffraction grating.

[0051]

Example 3

Next, an example of production of a DRAM device having a design rule of 0.1 μm using the exposure apparatus shown in Example 1 will be described. FIG. 11 mainly shows an exposure process of the manufacturing processes of the device.

[0052]

First, an isolation 202 and gates 203 were formed on a Si substrate 201 having wells (not shown) and the like formed thereon (FIG. 11a). The isolation and gate pattern were exposed by the exposure apparatus shown in Example 1 using a periodic phase shift mask. Here, since it was predicted by simulation that portions where the pattern shape is deformed may be formed on the periphery of the periodic pattern, a mask for removing the unnecessary portions was prepared. The mask was placed on the same resist film as that having been subjected to the exposure and exposed in an overlapping manner using the conventional exposure apparatus, and then, development was performed, and portions which are not desirable for circuit performance were removed. The unnecessary portions may not be removed but may be processed to be ignored by a circuit.

[0053]

Subsequently, a capacitor 204 and a contact hole 205 were formed (FIG. 11b). The contact hole pattern was exposed using a direct electron-beam writing method. Subsequently, first layer wirings 206, through-holes (not shown), and second layer wirings 207 were formed (FIG. 11c). The first layer wirings (0.1 μm L/S) were exposed using a periodic phase shift mask and the exposure apparatus shown in Example 1. However, in this case, the directions and dimensions of the respective diffraction gratings were changed to those shown in FIG. 9c, and the diffraction gratings were rotated by 90° and subjected to multiple exposures. At that time, the aberration correction filter 109 was also rotated by 90° together with the diffraction gratings. In this way, it was possible to form wirings extending in both vertical and horizontal directions so as to have a dimension of 0.1 μm L/S without any directional dependency. The through-hole pattern was formed by a direct electron-beam writing method similarly to the contact hole. Subsequently, a multi-layer wiring pattern and a final passivation pattern were formed by a general KrF excimer laser projection exposure method without using the present invention since the patterns were designed to have a design rule of 0.2 μm. The structure, material, and the like of the device are not restricted to those used in the example but may be changed.

[0054]

Example 4

Next, as another example of the present invention, an application example of production of a distributed feedback (DFB) laser will be described. As an exposure apparatus, an Arf excimer laser reduction projection exposure apparatus having an NA of 0.5 was modified similarly to Example 1 and used. In the conventional production process of a 1/4-wavelength shift DFB laser, diffraction gratings having a period of 140 nm which had been formed using an electron-beam writing method or the like were formed using a periodic phase shift mask and the exposure apparatus. In this way, it was possible to produce a DFB laser in a shorter time, which had performance substantially equivalent to that produced using an electron-beam writing method or the like.

[0055]

Effects of the Invention

As described above, according to the present invention, when a mask is irradiated with light by an illumination optical system, and a mask pattern is imaged on a substrate by a projection optical system to form the pattern on the substrate, a diffraction grating is provided between the substrate and the projection optical system in parallel to the substrate, and a diffraction grating or an imaging optical system is provided between the illumination optical system and the mask or between the mask and the illumination optical system so that an image of the mask pattern is reproduced near the substrate surface by the interference of light diffracted by the diffraction

grating. In this way, it is possible to form a fine pattern exceeding the resolution limit of the conventional exposure apparatus. Specifically, it is possible to obtain an effect substantially equivalent to that when the NA is substantially doubled at the maximum without changing the NA of the projection optical system. In this way, it is possible to obtain a large exposure field and a high resolving power without greatly changing the basic structure of the optical system of the conventional exposure apparatus and enable manufacturing of 0.1 μm-class LSI devices using reduction projection lithography suitable for mass production.

[0056]

Brief Description of the Drawings

FIG. 1

FIG. 1 is a schematic diagram geometrically showing the imaging principle of one optical system according to the present invention.

FIG. 2

FIG. 2 is a schematic diagram showing the imaging principle according to various conventional exposure methods.

FIG. 3

FIG. 3 is a schematic diagram showing the imaging principle when a phase shift mask or an oblique illumination method is applied to one optical system according to the present invention.

FIG. 4

FIG. 4 is a schematic diagram showing the imaging principle of one optical system according to the present invention from the perspective of diffraction optics.

FIG. 5

FIG. 5 is a schematic diagram showing a part of one optical system according to the present invention and an example of an exposure method.

FIG. 6

FIG. 6 is a schematic diagram showing the characteristics of one optical system according to the present invention.

FIG. 7

FIG. 7 is a schematic diagram showing optical elements used in the present invention and effects obtained therewith.

FIG. 8

FIG. 8 is a schematic diagram showing optical elements used in the present invention and effects obtained therewith.

FIG. 9

FIG. 9 is a schematic diagram showing a configuration of an exposure apparatus according to one example of the present invention.

FIG. 10

FIG. 10 is a diagram showing the characteristics of another example of the present invention.

FIG. 11

FIG. 11 is a schematic diagram showing a device manufacturing process according to another example of the present invention.

Description of Symbols

1	Mask
2	Projection Optical System
3	Pupil
4	Wafer
5, 20	Aperture
6, 29	Optical Axis
A, B, C	Diffraction Grating
R	Light
R0, R0'	0th Order Diffracted Light
R1, R+, R1"	+1st Order Diffracted Light
R1', R-	-1st Order Diffracted Light
A0, A1	Point on Diffraction Grating A
B0, B1	Point on Diffraction Grating B
C0, C1, C1'	Point on Diffraction Grating C
Q, P, Q'	Point on Image Plane
21	Conventional Transmissive Mask
22	Light
23	Projection Optical System
24	Pupil
25	Image Plane
26	Periodic Phase Shift Mask
27	0th Order Light of Mask-Diffracted Light
28	+1st Order Light
51	Image Plane
52	Light Shielding Mask
53	Crystal Substrate
O	Point on Mask
X_1, Y_1, Z_1	Point on Diffraction Grating A
X_2, Y_2, Z_2	Point on Diffraction Grating B
X_3, Y_3, Z_3	Point on Diffraction Grating C
I	Point on Image Plane
100	Mask Stage
101	Mask

102 Projection Optical System
103 Transparent Crystal Substrate
104 Wafer Stage (Sample Table)
105 Wafer
106 Transparent Crystal Substrate
107 Illumination Optical System
108 Transparent Crystal Substrate
109 Aberration Correction Filter
110 Stage Control System
201 Si Substrate
202 Isolation
203 Gate
204 Capacitor
205 Contact Hole
206 First Layer Wiring
207 Second Layer Wiring

FIG. 4(a)

Apparent Pupil Shape As Viewed From Point P on Image Plane Via Diffraction Grating B

FIG. 4(B)

Fourier Diffraction Images Obtained on Pupil And Travelling Directions of Light

FIG. 6(B)

Wavefront Aberration of Diffracted Light Having Diffraction Angle<0
Wavefront Aberration of Diffracted Light Having Diffraction Angle>0
Wavefront Aberration on Pupil
Normalized Pupil Radius Coordinate

FIG. 7

Diffraction Grating
Apparent Pupil Layout

FIG. 8

Diffraction Grating
Apparent Pupil Layout